# THE NATURE OF VOLCANOES.

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THE history of our understanding as to the conditions of volcanic action shows in a very clear way the steps by which a science is established. Among primitive folk, even when they have attained a considerable literary culture, the accidents of the earth, however striking, are taken as a commonplace manifestation of unseen powers—doings which need not be accounted for, or which may be explained by the will of gods or demons. Thus, in the Bible there is scarcely a trace of scientific curiosity, and none whatever of any enquiring motive such as has led to the rational interpretation of the natural realm. Vast and far-reaching as was the Hebraic spirit, it remained singularly unmoved by the events of the material world, looking upon them all as incidental and essentially unimportant, save as expressions of a Divine will.

The first clear trace of any questioning as to the nature of volcanoes, is found among the Greek philosophers. Between the seventh century, B.C., and the Christian era it is evident that enquirers were concerned with this matter, as they were with most evident problems of the earth. They attained to no success, in part because, though keen enough in guessing possible explanations of events, they never learned to criticise their conjectures, or, in the language of modern science, to verify their hypotheses. They were content with any idea which seemed to account for the facts. In larger part, their failure was due to lack of knowledge as to the nature of heat. By them heat was reckoned as an element, along with earth and water, among the primitive things that went to make up the world; so that when a volcanic explosion occurred it was to be explained as an outpouring of heat, much as a spring is of water.

Although our modern science is the child of Greek learning, it was a child of very slow growth. For more than a thousand years, the people of our Aryan race in Europe, though inclined to the study of phenomena, were so profoundly imbued with the Hebraic motive, and so much under the control of the Roman spirit, which was also completely separated from scientific interests, that no interpretation of Nature was essayed. It was not until the intellectual revolt called the Revival of Learning, in the fifteenth century, that the people of Western Europe began to question the world as to the laws of events, or to see in it more than good from the Creator's hand or evil from the interference of the devil and his imps. The scant knowledge of Nature which served as the foundations of modern science came almost altogether from the Greeks, and as mere fragments of the ancient learning. It provided little in the way of accurate information, and served not at all as a guide in methods of enquiry. The seeking spirit was happily native in our race and sprang swiftly into activity. The research work done by Leonardo da Vinci, fitly renowned as a painter and sculptor, but even more distinguished as an investigator, though unguided by earlier masters in its critical quality, foretold the best of our modern science.

From the Renaissance to near the end of the eighteenth century we find the nature of volcanic action the subject of much unavailing enquiry. The students of the problem were kept far from the truth, by the ancient notion that fire was a distinct element, one which was escaping from the depths. They came no nearer the truth than to suppose that some deep-lying burning material, such as coal, melted the rocks, and thus gave rise to the lava and gases which are poured forth in eruptions. Pictures in geological treatises of two hundred years ago show such fires in vast chambers, of which the roofs are the crust of the earth, through which the flames have forced a way to the surface by a crater. It was only when the part which oxygen plays in combustion was clearly recognized that it was seen that no ordinary process of burning could account for the evident facts, and that the study of volcanic action must proceed on other lines.

The first certain clue as to the cause of volcanoes was found when the outlines of the history of celestial spheres came to be discerned by astronomers—when it was seen that each of these bodies, suns, planets, and satellites alike, is in an early stage

of their development, intensely fluid, from heat, and that, parting with a share of their heat which goes forth into space, they in time come to be cold upon their surfaces though they may remain for ages intensely hot within. Applying this knowledge as to the general history of the spheres to the earth, geologists proceeded to explain volcanic eruptions by the supposition that they were due to the escape to the surface of some part of the ancient store of heated matter which lies below the frozen outer crust. This view, which was suggested in the later part of the eighteenth century, is evidently the basis on which a valid explanation of the complicated problems of volcanology must be founded.

Following the path of enquiry opened by the earth's ancient history given to them by the astronomers, students of geology began to seek the causes which lead to the violent ejections of heated materials from the depths of the earth. Curiously enough, it was only within the last century that observers came to recognize one of the most conspicuous features in all volcanic explosions, viz., the vast quantities of steam which always escape during such outbreaks. It had long been noticed that torrential rains usually attend on these explosions; but this was accounted for on the supposition that the water had gathered in caverns at the roots of the crater, and had been driven high into the air at the moment when the eruption began. Moreover, this stream, being commonly mingled with finely powdered rock, appears in the ejections of the cave as very dark-colored, often nearly black, a quite different hue from the unstained vapor of water. A close study of the matter showed that all lava, as it comes forth from the depths of the earth, is charged with steam. If we watch it near its exit, we see that the surface of the fluid boils furiously from the escaping vapor. Even after flowing for hours, every square inch of the surface shows from moment to moment the escaping bubbles. Next the very hot surface, the steam, being intensely heated, is perfectly transparent; as it rises and cools, it becomes more and more visible; and, at a considerable height, it forms the cloud-like wrap of vapor which hangs over the path of the flowing lava.

Further enquiry has clearly shown that the force which brings about a volcanic eruption is mainly, if not altogether, due to the expansive power of steam at the temperature, it may be, of 2,000° or more, Fahrenheit, and that, in large measure, the physical

condition of the ejected rocky matter, whether ashes, bombs, or flowing lava, depends upon the amount of this steam in the fluid rock and the temperature it attains. This can be most clearly illustrated, perhaps, by certain observations which I had an opportunity to make during a slight eruption of Vesuvius in 1882. At that time, the active cone was small, and the explosions were so limited in energy and so regular that, with a little care, it seemed possible to obtain a very near view of the process. Taking advantage of a strong northwest wind, which inclined the materials thrown out of the crater to one side of the cone, I approached the steep from the windward, unbombarded side.

On my way toward the active cone, I passed the well-known observatory, where there are instruments for measuring the earthquake shocks which such explosions send through the mountain. It did not need the insistent bobbing of the seismometers to indicate these quakings; they were evident enough to the senses miles away from the vent. I was told by the officers of the establishment that the energy of the movements had been for some time increasing, and that the cone would most likely be blown away in the course of a few hours. As there was no evident basis for this conclusion, I was not deterred by it. It was, in fact, years afterward before the change occurred; for then, as now, the conduct of a volcano eludes prediction. In company with my stout porter, who earned his wage by keeping his agreement to beat off his fellows who swarmed about, I gained the edge of the crater, with no other inconvenience than that which came from the violent shaking of the cone in the successive explosions, and from the strong gale which carried the ejected fragments of lava towards Pompeii. Once on the margin of the crater, with my face protected by a paper mask, it was possible for me to look down into the pit and to see, perhaps nearer to the seat of an eruption than any other geologist has had a chance to do. The conditions were not favorable for careful observation. The heat was almost unendurable, and the air at times so charged with steam and sulphurous fumes as to be suffocating. Moreover, at most of the successive explosions I was thrown backwards down the ash-covered slope, before I had a chance to note just what happened; yet the effort was not altogether fruitless, for I beheld certain features which threw light on the processes of an eruption. These features I will now describe.

The pit of the crater was several hundred feet in diameter and one or two hundred feet deep: there being nothing in view that would serve as a scale for measurement, its size could not be well determined. The inner slopes of the cavity led down, in the manner of a funnel, to a well-like shaft, about sixty feet in diameter, which descended nearly vertically. The upper part of the funnel was not hot enough to glow, but about the lower third it was of a dull red heat, and thence downward of a brighter hue, until, in the vertical shaft, it glowed like the eye of a furnace. About four or five times a minute, this shaft, usually empty, was partly filled with white, very fluid, hot lava, apparently as fluid as water, which rushed swiftly upward until it occupied the lower part of the crater to the depth of forty feet or more. Then the whirling pool swelled like a huge bubble which burst open, so that the broken masses of lava were driven upwards as if shot from the mouth of a cannon. The action was very swift, so that from the time the lava came in sight in the shaft, perhaps fifty feet below the base of the funnel, to the instant of the explosion was not more than three seconds. As soon as the discharge occurred, the lava not blown out fell back out of sight into the depths of the shaft.

Although, as before remarked, it was not possible narrowly to observe just what occurred at the moment of the successive explosions, for the reason that the shocks generally threw me away from the edge, some of them being less intense than others I managed to get a sufficiently clear view of the process. It was evident that the explosion was due to the escape of gas or vapor at a very high tension. At the moment of explosion, the cavity below the rent surface was apparent. The impelling vapor was at first perfectly transparent; in a moment, however, it took on a steel-gray hue, and in a second or two had the whitish color of steam. As the cloud swept about me, it was perfectly evident that it was the vapor of water with some sulphurous gas, and probably some chlorine and other gases. In four or five seconds, the strong air currents due to the heat and the gale of wind drove the steam out of the pit, so that all parts of it were clearly visible. I reckoned the speed of ascent of the fragments that were cast upward as at least four hundred feet a second. The time that elapsed between the bursting of the bubble and the crash of the falling masses on the further side of the cone, indi-

cated that they rose to the height of more than fifteen hundred feet above the point of discharge. My observations at the crater were suddenly interrupted by a lull in the gale which had made them possible. Masses of the lava, some of them as large as nail kegs, began to fall near me so that I had to retreat, and that speedily. My valiant porter objected to my haste, saying that there was no grave danger, for the chunks of lava were *soft!*

All that was visible in the crater whence this slight but instructive eruption came bore out the supposition that the motive power of volcanic outbursts is steam. Much else that could be seen was to the same effect. Thus, as the fragments of lava, whirled up at each explosion, swept through the air, their surfaces cooled, so that when they came back to the ground they had a darkened crust. As they burst open at the moment of contact with the earth, they visibly ejected steam. A small stream of lava flowing from the cone poured forth steam from every part of its surface. As the fragments sent up by the explosion rose in the air, they were enveloped in a cloud of steam, which, as it drifted away, yielded a little rain.

After I left the cone, the explosions—at first, as above noted, not more frequent than four or five per minute—came at shorter intervals, until, for a time, the discharge seemed as continuous as that from a locomotive moving at high speed,—where we know that, for all the seeming continuity of the action, the outrush of vapor takes place by successive jets, the intervals being too brief for ear or eye to note them. This, like much other evidence, goes to show that the eruptions of a volcano are essentially like boiler explosions, where steam at high temperatures rends the walls which restrain it. The tumult of the greater outbreaks arises from innumerable rupturings such as occurred at distinct intervals in the very small instance above described. It is furthermore evident that the water which impels the ejection is in most, if not all, instances very intimately mingled with the rock which, when melted, forms the lava. When the eruption is so violent that the lava is brought suddenly from the depths of the earth, as is the case in all considerable outbreaks, the lava is blown into a dust finer than can be produced by any process of grinding rock. Thus, in the explosion of Krakatoa in 1883, the dust was in such minute particles that much of it floated for three years, all the earth about, before it came to rest; and some

part of it appears to have gathered into what were called "shining clouds," which gradually rose higher and higher until they seemed to escape from our atmosphere. Such dust has been known to bring midnight darkness at mid-day more than a thousand miles from the volcano that poured it forth. This measure of comminution from exploding steam indicates that the water was very completely mingled with the rocky matter before it was heated.

Where the ascent of the lava to the surface is more gradual than it is when the material is rent into dust, the water appears to gather into aggregates, so that the explosion produces larger fragments looking like grains of sand or having a pebbly form and size. As the violence of the movement is still further reduced, the steam has a chance to boil out of the lava, which then accumulates in the crater, or in the pipes below its level, until it breaks its way through the heap of cinders of which the cone is composed, and flows away as a stream. When, as in the great volcanoes which remain permanently in eruption, the boiling lava remains long in the cup, it may part with nearly all its steam; but in all cases it is evident that this vapor is the mainspring of volcanic action.

Taking it as proved that volcanic explosions are essentially due to the expansive force of steam at a very high temperature, the next question which geologists have to face concerns the method by which the water obtains access to the rocks, and becomes intimately mingled with the materials of which they are composed. On this point there is as yet no agreement; some students of the matter hold that the water in question passes downward from the surface to the heated depths, and there coming in contact with the molten rock is converted into steam. This view is clearly untenable, for the reason that, as we have seen, the water is perfectly mingled with the lava; a condition which could not be brought about by a mere contact with heated rock on its way to become lava. The least generation of steam under these conditions would tend to expel the descending water through the passages by which it entered the earth. It is true that surface water accumulating in the fissures beneath a long silent cone may be suddenly vaporized by an ascent of lava when the activity of the volcano is resumed. Many eruptions begin by the ejection of large quantities of water, which may be thus accounted for.

But this in no wise helps us to explain the mingling of water with the molten rock, which is the key to the problem of its ejections, and is, as we shall see, the clue to many other important questions in volcanology.

To determine the steps by which the water of lavas finds its way into the fluid rock, we need to set about the task in the manner of the modern naturalist, as Leonardo did his work and thereby showed how such work should be done. We should note, in the first place, how volcanoes are distributed over the earth. This distribution is evidently peculiar; as is shown by the fact that, until our acquisition of Alaska, there was not a single cone in the United States which had been distinctly active in recorded time. The records clearly show that of the many hundreds, if not thousands, of volcanic cones which have been seen to discharge, all are in the sea or near thereto, not one of them being as much as three hundred miles inland. Furthermore, the geological history of the multitude of now extinct volcanoes in the heart of the continents, shows that, in general, the cessation of their activity was coincident with the disappearance of broad waters from their neighborhood. It is, in a word, evident that there is some casual relation between what takes place beneath the seas and the existence of volcanic activity.

The fact that active volcanoes are limited to the ocean floors and to the parts of the great lands lying near thereto, has been taken by some enquirers to be evidence that it is to the downward penetration of water that we are to attribute, in the manner above noted, the presence of the fluid in lavas. The fact is, however, that water must enter the under-earth more readily on the land than beneath the sea-floor; for on the land area we have an extensive river surface, especially in mountainous districts, while on ocean bottoms there is practically everywhere an essentially impervious sheet of recent and unbroken deposits through which water cannot pass. The true basis of the relation is to be found in quite another series of actions, which may be briefly set forth as follows:

Let us first note that, from the depths of the earth, heat in large quantities is constantly and everywhere passing forth into the cold spaces that wrap in the sphere. Each year, enough heat thus creeps upward through the blanket of rocks, if it could be held in the crust, to raise the temperature of a layer of any

ordinary stone a foot in thickness by some degrees of temperature. Now, beneath the sea-floor, strata are normally accumulating at a geologically rapid rate; and every layer, because it is a non-conductor, serves to retain this heat, as does the mineral wool covering in a boiler or the "cosset" on a tea-pot. The result is, that a layer of rock laid down many geological periods ago on the cool surface of the ancient ocean floor, say at 40° Fahrenheit, if covered by successive strata to the depth of 100,000 feet, will acquire a very high temperature, probably somewhere near 2,000°, Fahrenheit. We see by the remnants of strata which are exhibited on the land that even much greater thicknesses of deposits may be heaped up over wide areas. Now, let us remember that, as beds of any kind are laid down in water, they are always made up of fragments; and between these bits are spaces which are filled by the fluid; and, furthermore, that the bits themselves are water-soaked. This water, as I have found by extended enquiry, amounts in different kinds of strapped rocks to from one-twentieth to one-fifth of their mass. Given this water, and the heat which must come to it with deep burial, and we have the fundamental conditions of a volcanic explosion—conditions which do not exist beneath the lands where the blanket of strata is always wearing away (with the result that the temperature of the underlying rocks is ever lowering), and which exist only beneath the great water areas, where strata are accumulating and, as a consequence, the deep-buried water is ever becoming hotter and ever straining more vigorously on the rocks that case it in.

As for the ways in which volcanic vents are opened, and the details of the process by which the imprisoned water finds its way to the surface, driving with it the melted rock in which it is contained, our knowledge is yet limited. It is clear, however, that many if not most volcanoes are situated along those lines of fracture of the earth's crust termed "faults,"—breaks which may extend from the surface downward for many miles of depth. These fractures often are so placed that they traverse coast lines, so that the volcanic materials produced beneath the sea floors may find their way to the air on neighboring continents. This arrangement of volcanoes along great breaks in the strata, accounts also for the fact that, when a volcano on one part of the rift becomes active, others on the same line are likely to erupt, as has been the case in the vents on Martinique and St. Vincent.

It is from many such instances evident that the movements of the heated rocks which feed one crater—movements of much violence—are likely, by the resulting shocks, to awaken a train of convulsions which may propagate the action far from its original source.

It is to be borne in mind that, when extremely heated rocks containing water are penetrated by a fault, the expanding steam will force the whole mass in movement towards the place of escape—as in the instance of dough, where the yeast fermentation produces gas, the material creeps in the direction of least resistance. When the rocks start on their enforced journey they are probably solid, kept in that state by the vast pressure of the beds above them, but as they arrive near the surface, they become softened and finally, it may be, as liquid as molten glass. The evidence goes to show that the lavas and ashes which are poured from the greater volcanoes are often derived from locations hundreds of miles away from the vent by which they escape. Thus, while the materials thrown out by Aetna have probably amounted to a bulk of more than a thousand cubic miles, the foundations of the cone have gradually risen since ejections began, until now its base is some hundred feet higher than at the beginning. This clearly indicates the remote derivation of the erupted matter.

The foregoing account of the steps by which our knowledge of volcanic action has been won is but a sketch. It takes no account of sundry hypotheses and conjectures, which have had their place in the procession of ideas, but have not helped the progress of geology. It neglects the problem of the moon's so-called volcanoes, for the reason that those remarkable structures, though vents of ejection, are clearly not really comparable to those now existing on the earth. Even this inadequate story shows how, step by step, by the interaction of the several physical sciences, the enquiries of geologists have slowly won a share of truth—truth as yet incomplete in this as in other fields, but sufficient to make the earth rational to our understanding.

Turning now to the recent calamitous eruptions of Martinique and St. Vincent, let us see what light our knowledge of volcanic action turns upon these events. It is, in the first place, evident that these eruptions, frightful as they have been in their effect on human interests, are of relatively slight physical importance. The intensity of a volcanic outbreak may be approximately

measured by the distance at which the sounds produced are heard. In the greater eruptions, such as that of Krakatoa, the most violent explosions were audible two thousand miles or more away from their source. In the Martinique eruption, they appear to have been heard at a distance of no more than two hundred miles. As the energy of the shock to air and earth is roughly proportional to the areas affected, it appears that the former disturbance was at least a hundred times as violent as the latter. The measure of energy expended in the outbreak of Mt. Pelée and the amount of the materials thrown out, or the distance to which they were hurled, do not, from the information now at hand, appear to have been anything like as great as in the case of many Vesuvian eruptions, and are not to be compared to the cataclysms of the Javanese archipelago and those of Iceland, or even with the explosions of Aetna. To what, then, may we attribute the unexampled magnitude of this calamity; for in no other well-attested eruption has the loss of life been so great?

A glance at the position of St. Pierre in relation to the volcano which destroyed it shows that the city lay within four or five miles of the cone, and on the side whereto the prevailing winds would be likely to drive the vapor and ashes from the crater. The ash ejected appears to have been mainly of a coarse nature, and the quantity of volcanic bombs—that is, masses of lava, which, whirling, take on a rudely spherical form—more than usually great in quantity. The falling ash apparently served to force the heated air and steam down upon the surface, so that it flowed over the town, while the bombs, molten lava within, though hard crusted without, were as effective as hot shot in carrying heat and setting fire. It is probable that, in this as in other eruptions from long-dormant volcanoes, much carbonic-acid gas, which had gathered in the caverns at the base of the cone, was mingled with the steam and sulphurous fumes, the whole forming an irrespirable air which quickly and mercifully suffocated the stricken folk. In some instances, this tide of mephitic vapors has been known to destroy all life for a radius of many miles about the point of discharge. Thus, while the accident appears to have been in a geological sense relatively unimportant, the position of the town in relation to the cone, the neighborhood of sea which barred flight, and the somewhat unusual swiftness in the development of the outbreak, combined to make it a very great calamity.

There are certain lessons to be drawn from the disasters of Martinique and St. Vincent. The first of these is that the neighborhood of a volcano that has been so recently in eruption as to retain its shape in a well-preserved state, is not a fit place for a city or other important seat of man's endeavors. The second concerns the importance of systematic and extended observations of volcanoes, with a view to an effective foretelling of approaching eruptions. So far, observations of this nature have been limited and imperfect. There is reason to believe that it will neither be difficult nor costly to obtain data such as would have spared the thousands who died in the recent disasters. It is clearly not in the power of man to prevent the activity of volcanoes, as he well may the vastly more destructive plagues of war and disease; but he may by his understanding lessen the evils they inflict, as he does those of the hurricane or the earthquake. It is well to note, however, that the calamities which may thus be avoided, though in their nature appalling, constitute but an insignificant part of the sum of death and destruction that comes to man. Though this earth beneath our feet is the seat of titanic forces, it deals gently with its living tenants—far more gently than they with one another. That life is here as the result of at least a hundred million years of uninterrupted progress, shows that the interference of the powers of the under-earth with the course of life has not been serious.

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